Expanding the Gravitational Wave Frontier: Detecting Exceptional Binary Black Hole Mergers with a Model-Independent Search

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Relativity and Gravitation Seminar
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University of Warsaw
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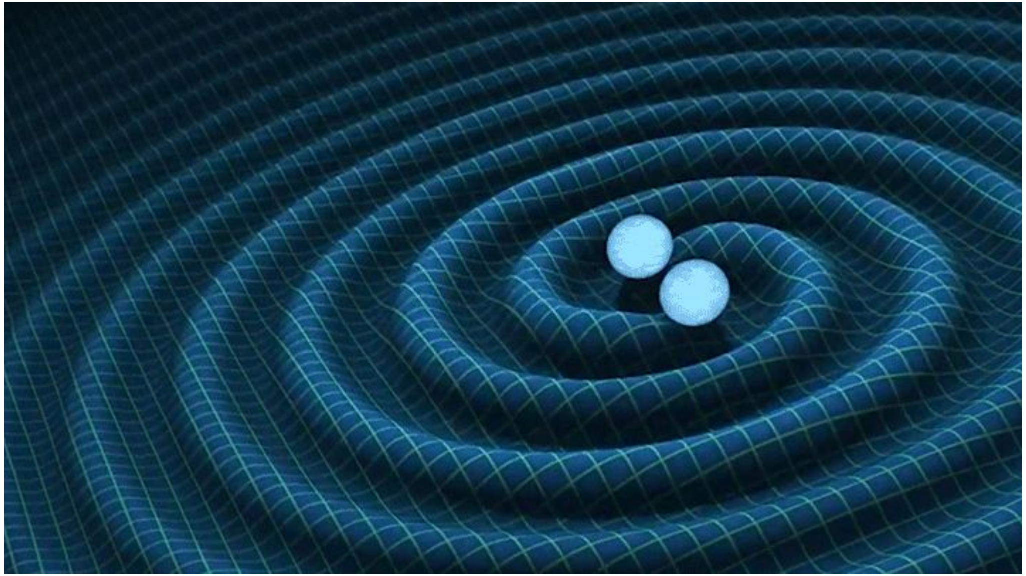
Gravitational Waves (GW)

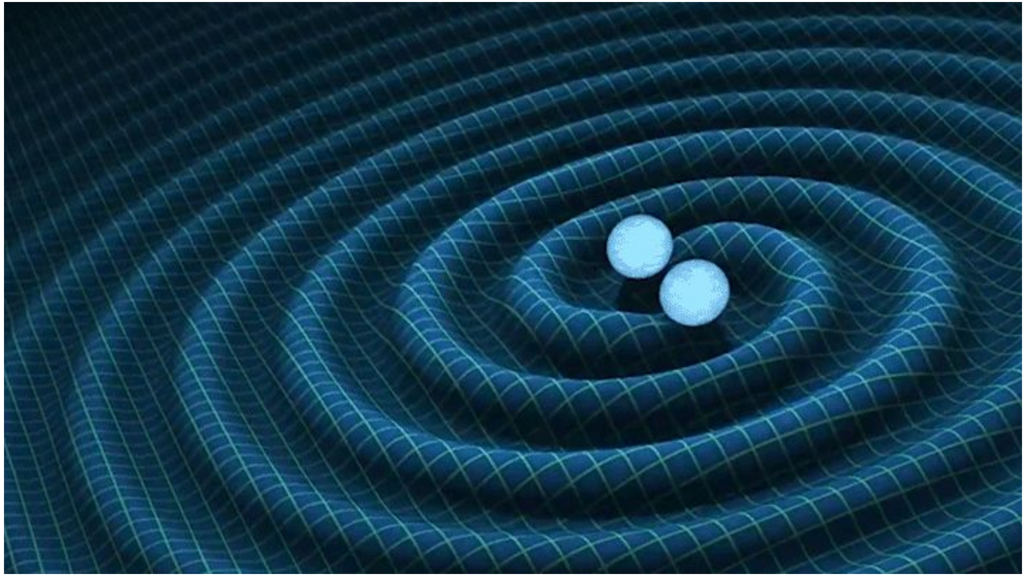
- Predicted by Einstein in General Relativity (GR).
- Accelerating masses emit GW.
- Time variation of the mass quadrupole moment.
- Transverse waves of spatial strain: plus and cross polarization.



An artist's impression of GWs emitted by a Binary Neutron Star (BNS) system *[R. Hurt/Caltech-JPL]*.

Gravitational Waves (GW)

- Predicted by Einstein in General Relativity (GR).
- Accelerating masses emit GW.
- Time variation of the mass quadrupole moment.
- Transverse waves of spatial strain: plus and cross polarization.
- **Terrestrial sources produce GW with strain amplitude too weak to detect.**



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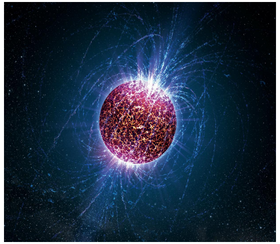
Sources of GW

Long Duration

Continuous

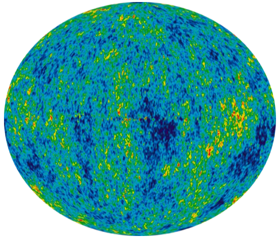
Rotating Neutron Star (NS) with surface imperfections.



[C. Reed, Penn State]

Stochastic

Cosmic GW background from the early universe.

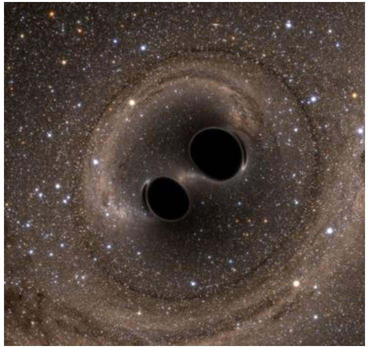


[NASA/WMAP Science Team]

Short Duration

Compact Binary Coalescence (CBC)

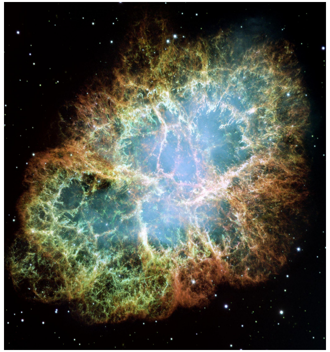
- Binary Black Hole (BBH)
- Binary Neutron Star (BNS)
- Neutron Star - Black Hole (NSBH)



[SXS Project]

Burst

Core-Collapse Supernova (CCSN).



[NASA, ESA, J. Hester, ASU]

Modeled *Unmodeled*

Sources of GW

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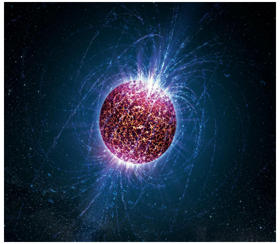

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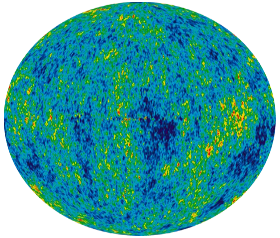

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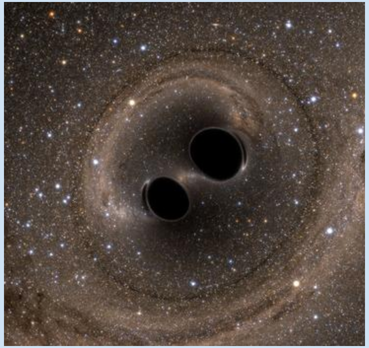
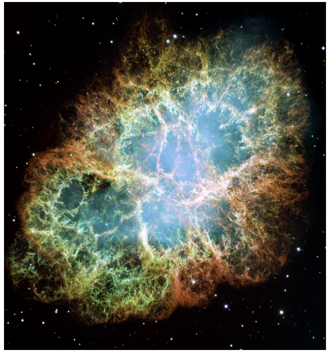


[SXS Project]

90 CBC signals detected by ground-based detectors!

Burst

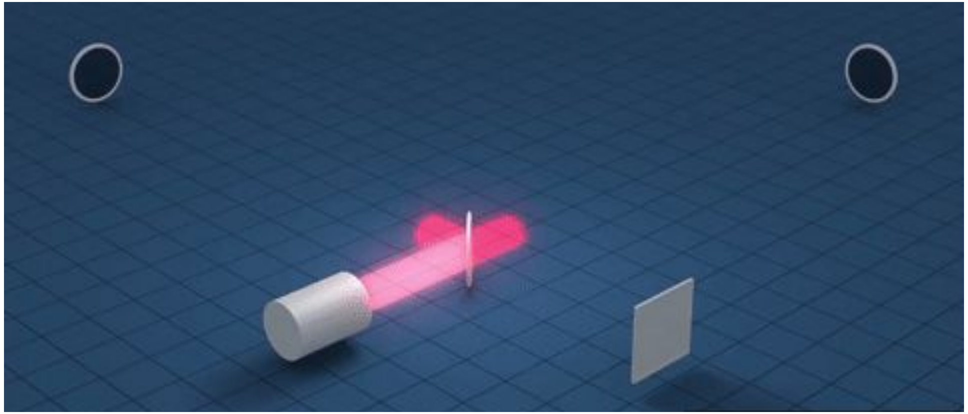
Core-Collapse Supernova (CCSN).



[NASA, ESA, J. Hester, ASU]

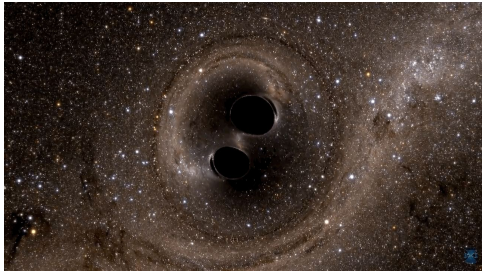
Modeled *Unmodeled*

Detecting GW Signals from CBC

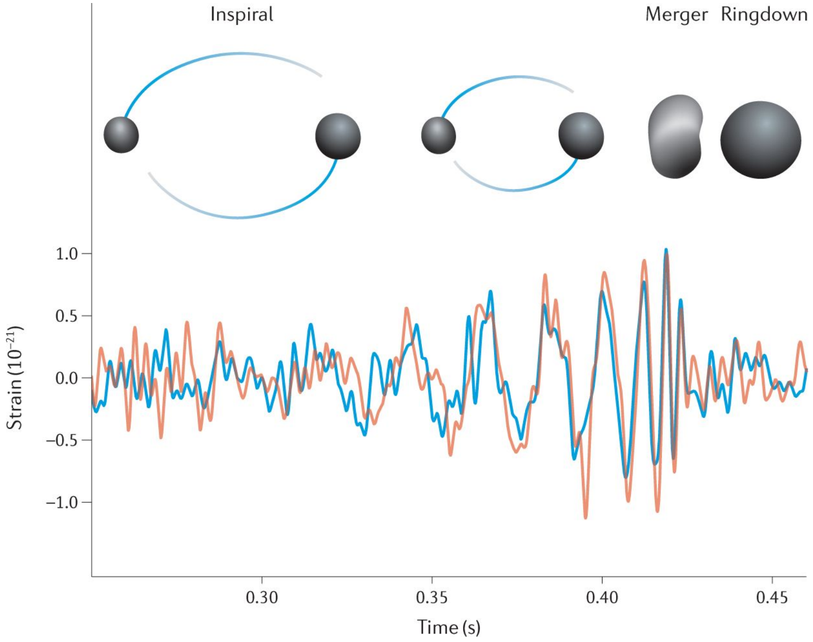


[T. Pyle, Caltech/MIT/LIGO Lab]

$$h = \frac{\Delta L}{L}$$

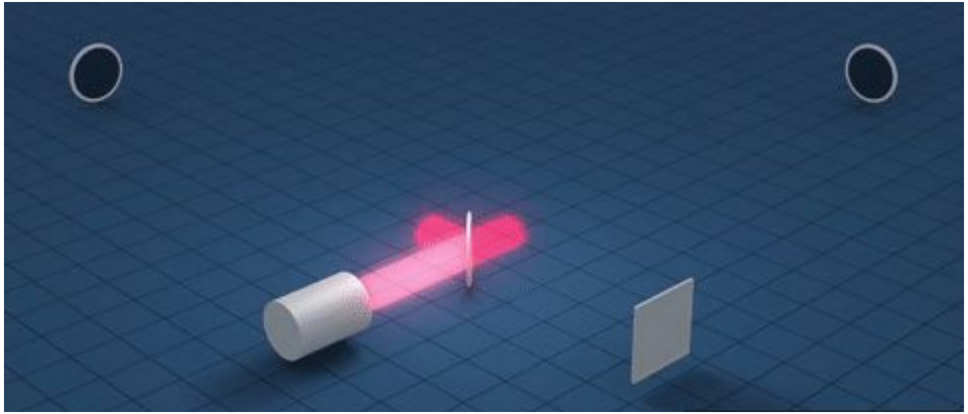


[SXS Project]



[Phys. Rev. Lett. 119, 161101]

Detecting GW Signals from CBC



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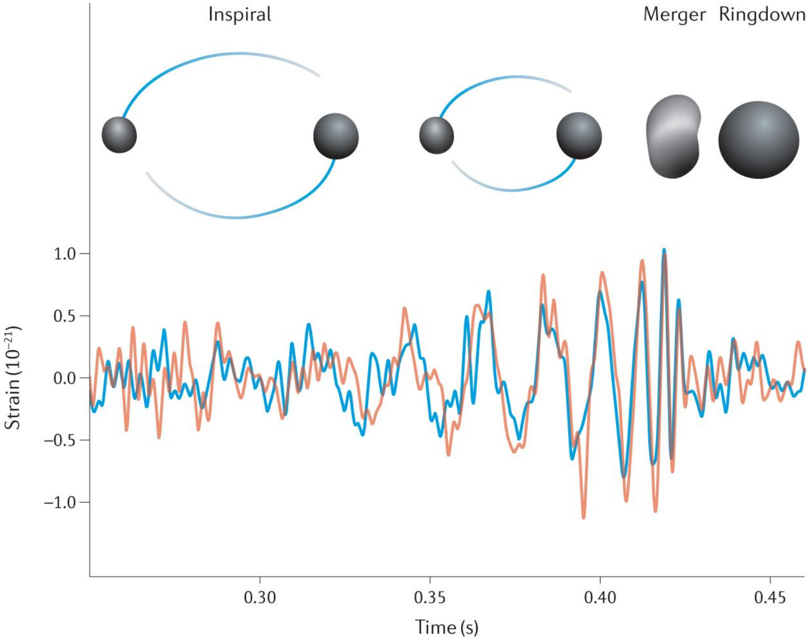

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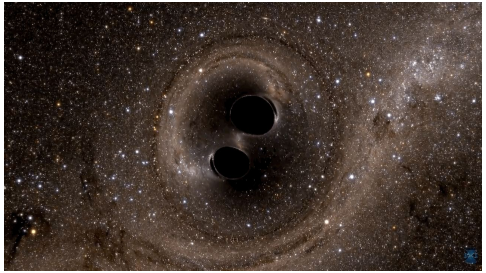

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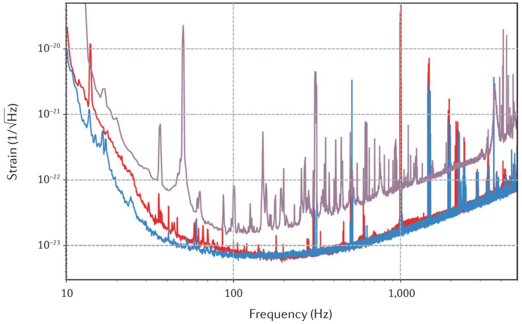
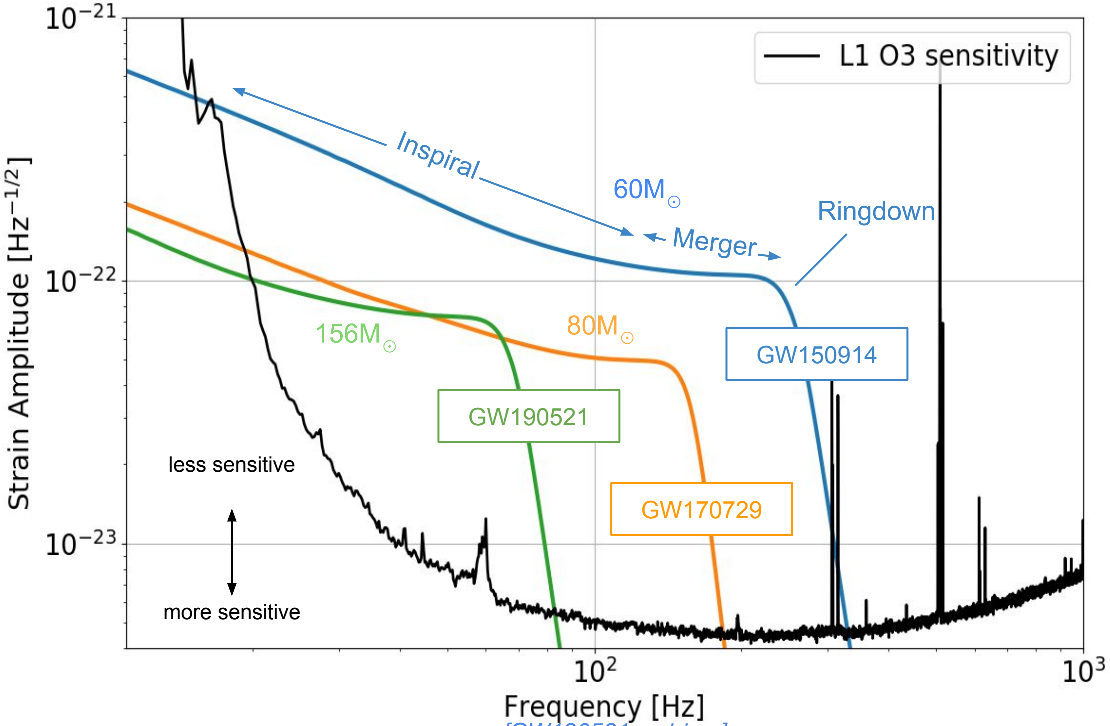


[Nature Reviews Physics 3, 344-366 (2021)]

LIGO Detectors

Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors at Hanford (H1) and Livingston (L1).



[GW190521 webinar]

- Each detector has two 4km long arms, setup like a Michelson interferometer.
- Extreme sensitivity attained of the order of $h=\Delta L/L \sim O(10^{-23})$ which is the expected gravitational wave strain from an astrophysical source.
- LIGO sensitive frequency band 10Hz - 1000Hz.
- LIGO- Virgo-KAGRA (LVK) collaboration has detected 90 CBC signals so far *[GWTC-3]*.

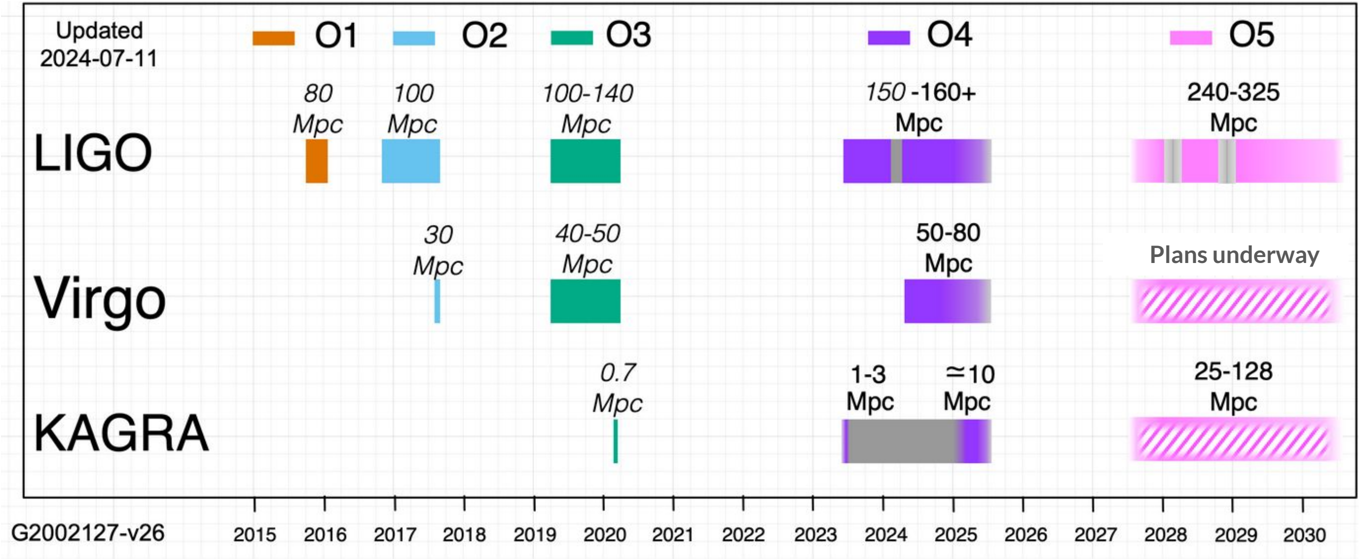
Gravitational-wave Network

Underground detector.

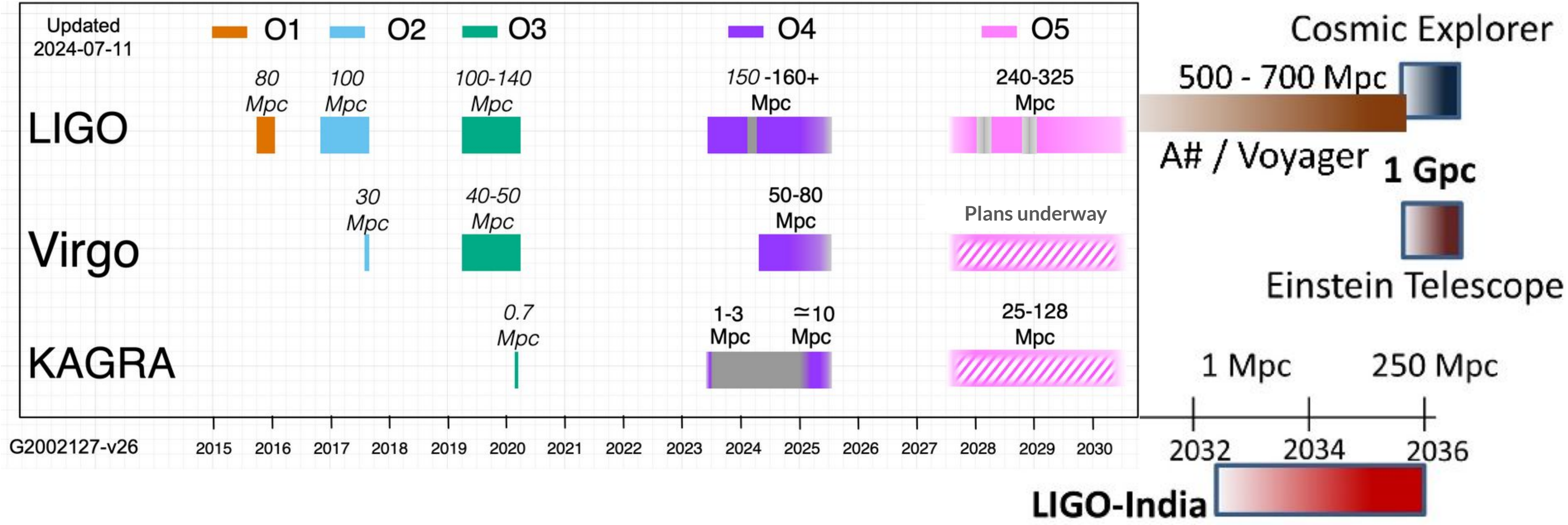
A third LIGO detector in India (2032/2036)

Gravitational-wave Network

GW Sensitivity Across Observing Runs

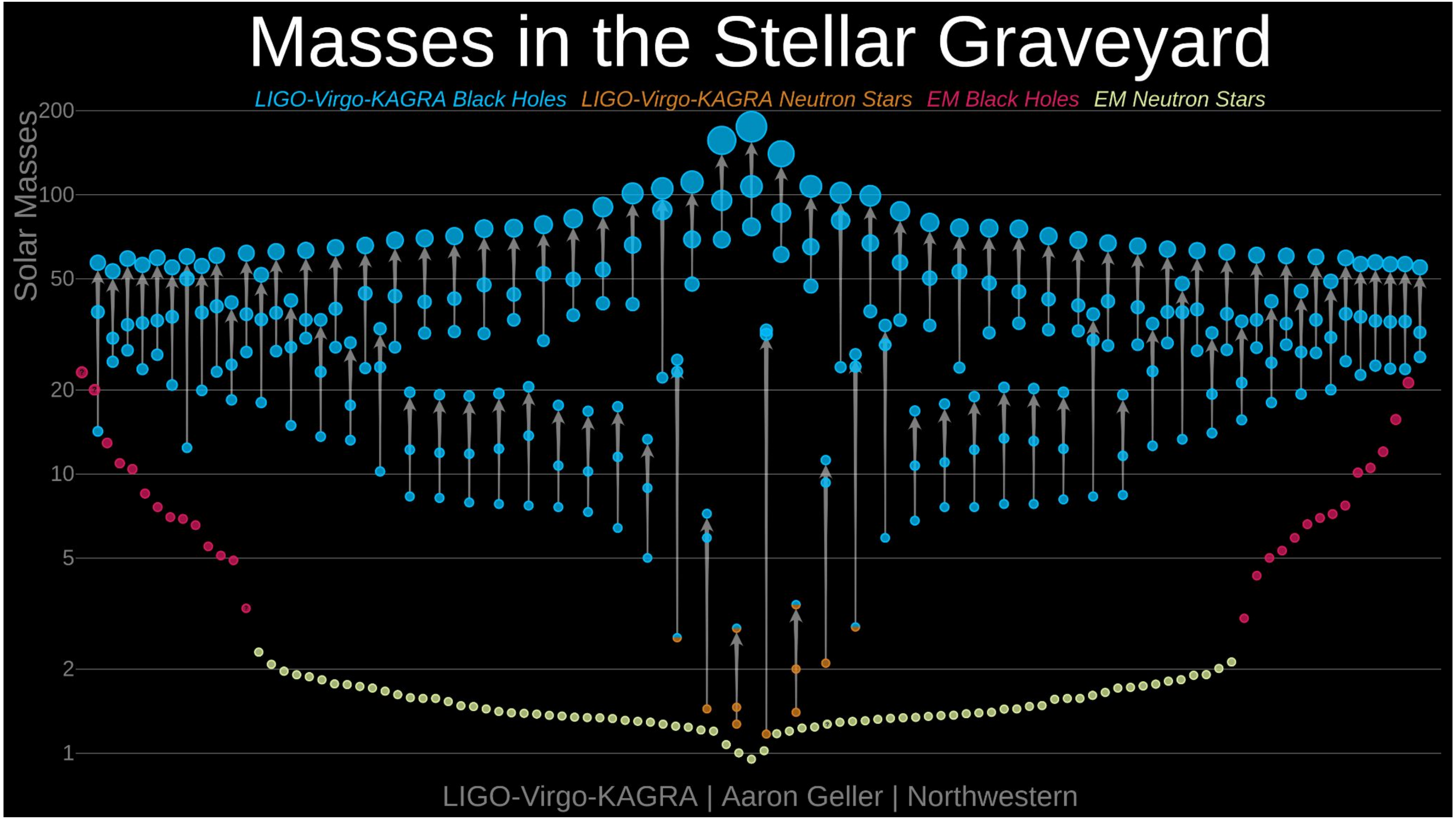


GW Sensitivity Across Observing Runs



What have we seen so far?

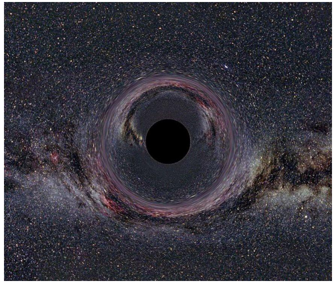
GW Detections from the First Three Observing Runs



Intermediate Mass Black Holes (IMBHs)

- Black holes (BH) with masses in the range $100\ M_\odot$ - $10^5\ M_\odot$.
- Missing link between stellar mass ($< 100\ M_\odot$) and supermassive ($> 10^5\ M_\odot$) BH.
- Various IMBH candidates proposed from EM observations, empirical mass-scaling relations, hyper-luminous X-ray sources, but aren't conclusive.
- Most massive BH observed via GW in the third observing run (O3) of LIGO - **GW190521** event.
  - First conclusive evidence of IMBH $< 10^3\ M_\odot$, with its total mass $142\ M_\odot$ (component masses $85\ M_\odot$ and $66\ M_\odot$).
- Primary component of GW190521 - interesting candidate with far-reaching astrophysical implications.

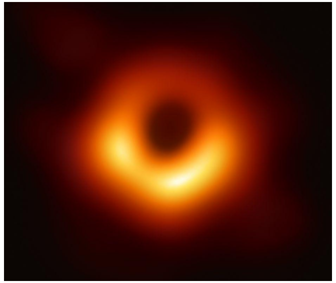
Stellar mass BH $< 100\ M_\odot$



[Ute Kraus/Wikipedia, CC BY-SA]

$100\ M_\odot$ < IMBH < $10^5\ M_\odot$

Supermassive BH $> 10^5\ M_\odot$

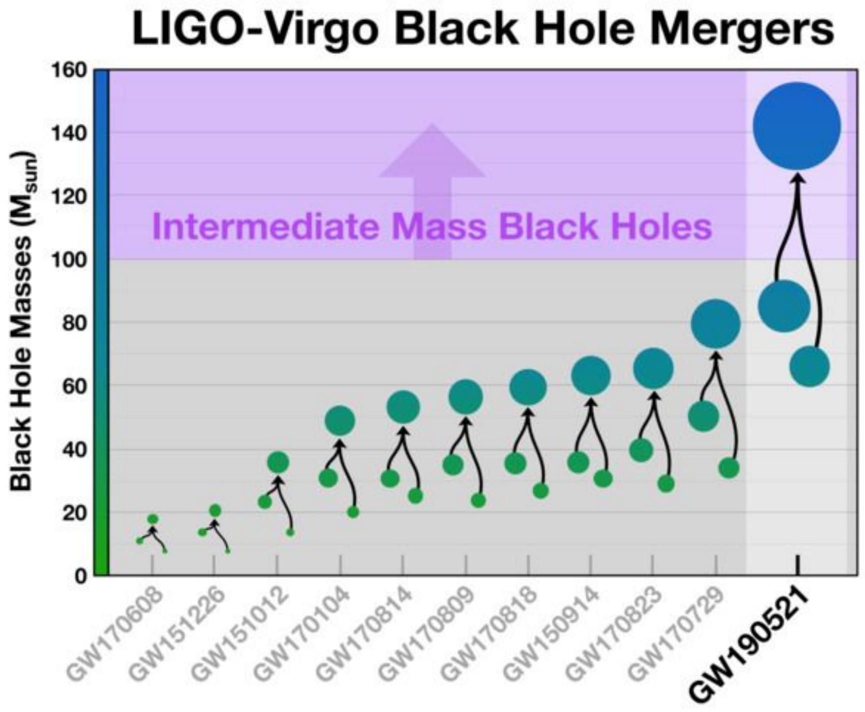


[Event Horizon Telescope]

Pair Instability Mass Gap

Sufficiently heavy He core mass can provide suitable conditions for abundant pair production (electron-positron) which causes the star to violently implode.

- Stars with He core mass in (32 $M_\odot$, 64 $M_\odot$) - pulsational pair instability supernova (PPSN) - remnant BH mass < 64 $M_\odot$.
- Stars with He core mass in (64 $M_\odot$, 135 $M_\odot$) - pair instability supernova (PISN) - no compact remnant (PISN mass gap).
- Stars with He core mass > 135 $M_\odot$ directly collapse to form an IMBH.



Masses of the GW detections from first and second observing runs (O1 and O2) of LIGO + GW190521 event. *[LIGO/Caltech/MIT/R. Hurt (IPAC)]*.

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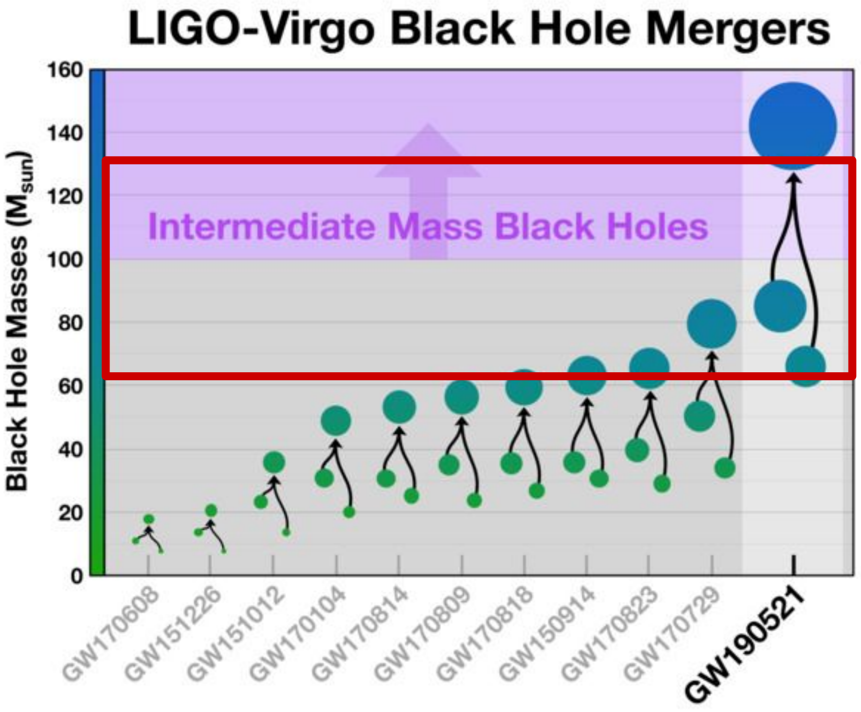
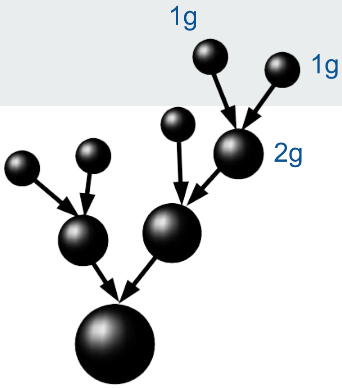
Primary component BH of **GW190521 lies in the PISN mass gap** and can't be a SN remnant - raises questions on the possible formation channels.



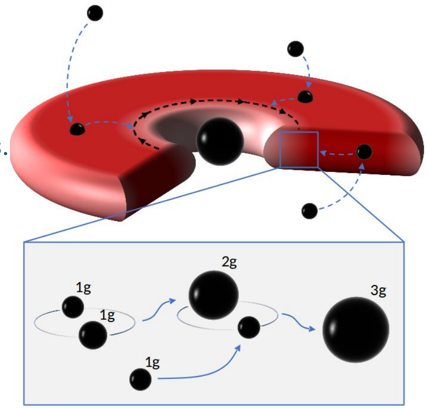
Masses of the GW detections from first and second observing runs (O1 and O2) of LIGO + GW190521 event. *[LIGO/Caltech/MIT/R. Hurt (IPAC)]*.

Possible Formation Channels

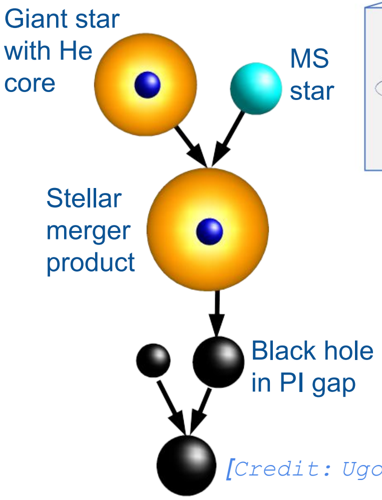
- **Hierarchical mergers:**
  - Mergers involving one or two second generation (2g) BHs.
  - First generation (1g) merger of BHs can produce a 2g BH in the PISN mass gap.
  - Triple systems or dynamic capture in a dense cluster.
- **Active Galactic Nucleus (AGN) disk:**
  - Dense and hot environment hosting *O*(10,000) BHs.
  - BBH mergers are expected to stay in the AGN disk and acquire another companion BH.
- **Stellar merger scenario:**
  - Star with over-sized Hydrogen envelope.
  - Direct collapse into BH in the PISN mass gap without encountering PISN/PPSN.
  - Merger with companion main sequence star required to get over-sized H envelope.



Different merger scenarios. [GW190521 webinar].



[Credit: Imre Bartos]



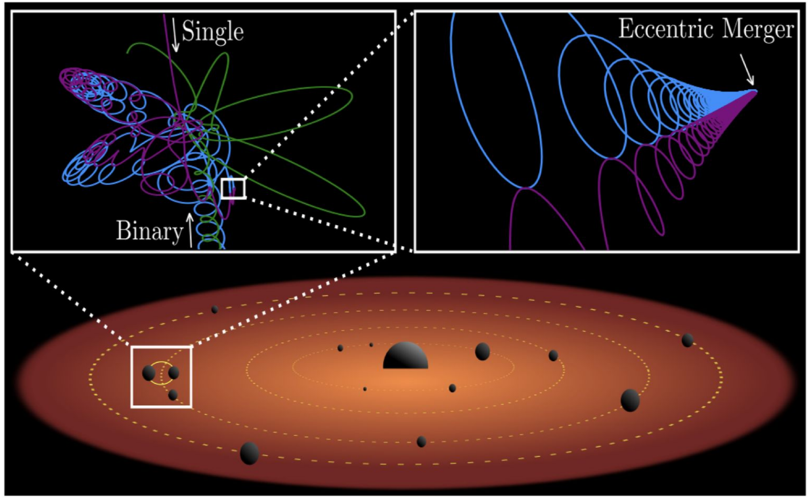
[Credit: Ugo N. Di Carlo]

How do we distinguish between formation channels?

The Role of Eccentricity

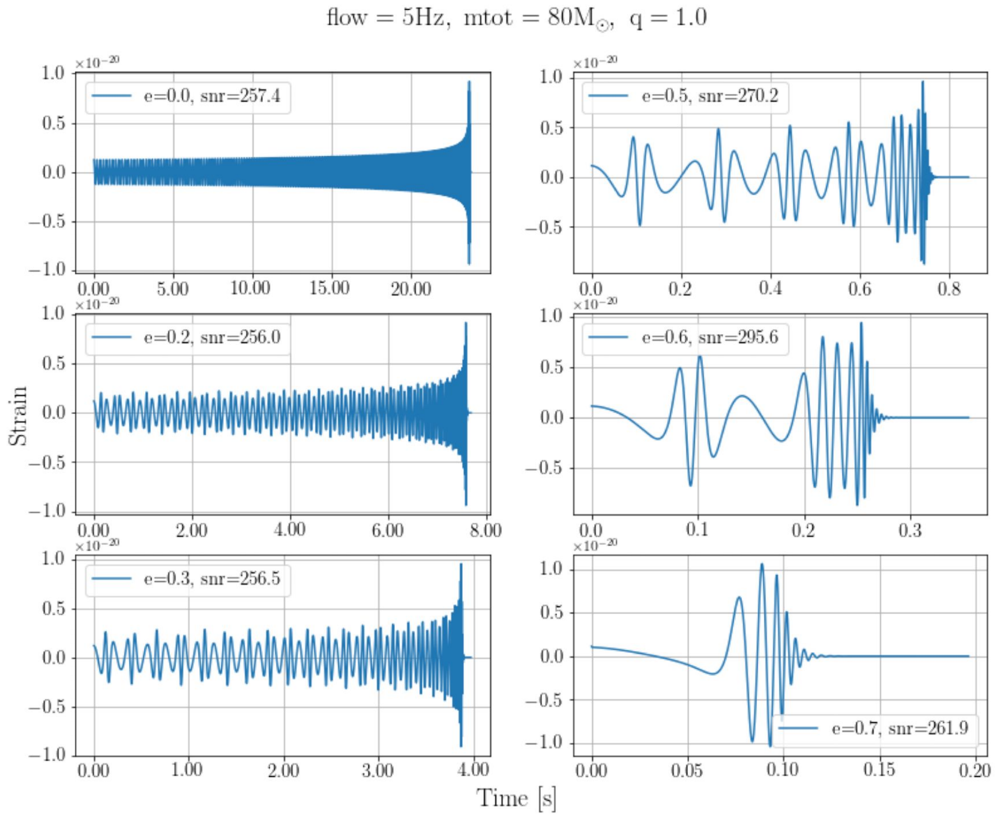
Orbital eccentricity is a key signature that points to dynamical formation!

- **Isolated field binaries:** long-lived binaries circularize -> Negligible eccentricity *[Peters, 1964].*
- **Dynamical formation:** Dynamically formed binaries merge rapidly -> retain eccentricity *[Zwart and McMillan, ApJL 2000]*.
- **Kozai-Lidov Mechanism:** Binary system perturbed by a third body *[Fragione and Kocsis, MNRAS 2022]*.
  - Oscillations in eccentricity and inclination of the inner orbit.
  - High eccentricity -> GW bursts -> binary system merges quickly -> retains eccentricity.
- **Mergers in AGN:** Binary-single interactions within the disk are frequent, lead to eccentric mergers *[Samsing, Bartos et al., Nature 2022]*.



AGN disk with a central supermassive black hole and smaller black holes orbiting it *[Samsing et al. Nature, 2022]*.

Gravitational Waves from Eccentric Binary Mergers

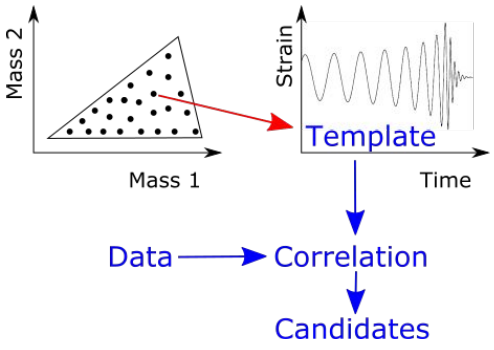


- Dependence of signal morphology on orbital eccentricity.
- GW amplitude does not rise monotonically with time for eccentric mergers.
- As eccentricity is increased, the signal duration becomes shorter.

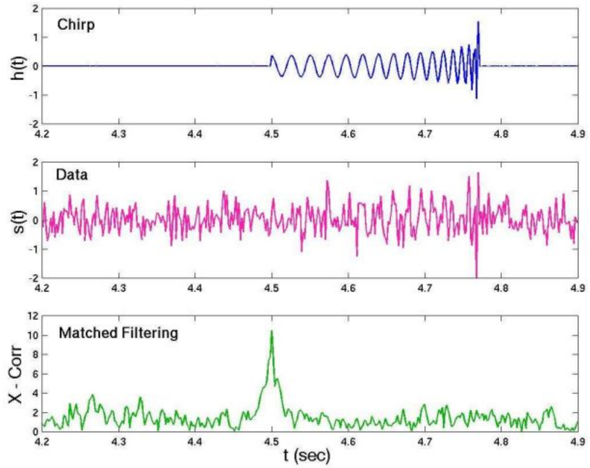
Searches for Gravitational Waves

Search Types

- **Modeled Search:**
  - Looks for sources that are well modeled.
  - Accurate waveforms are used to construct template banks e.g. CBC.
  - Uses Matched Filtering, example - PyCBC, GstLAL.



- **Unmodeled Search:**
  - Looks for sources with minimal dependence on accurate waveform models.
  - Can detect unmodeled sources e.g. CCSN and poorly modeled CBC sources.
  - Searches for excess power in the time-frequency domain, example - Coherent WaveBurst (cWB).



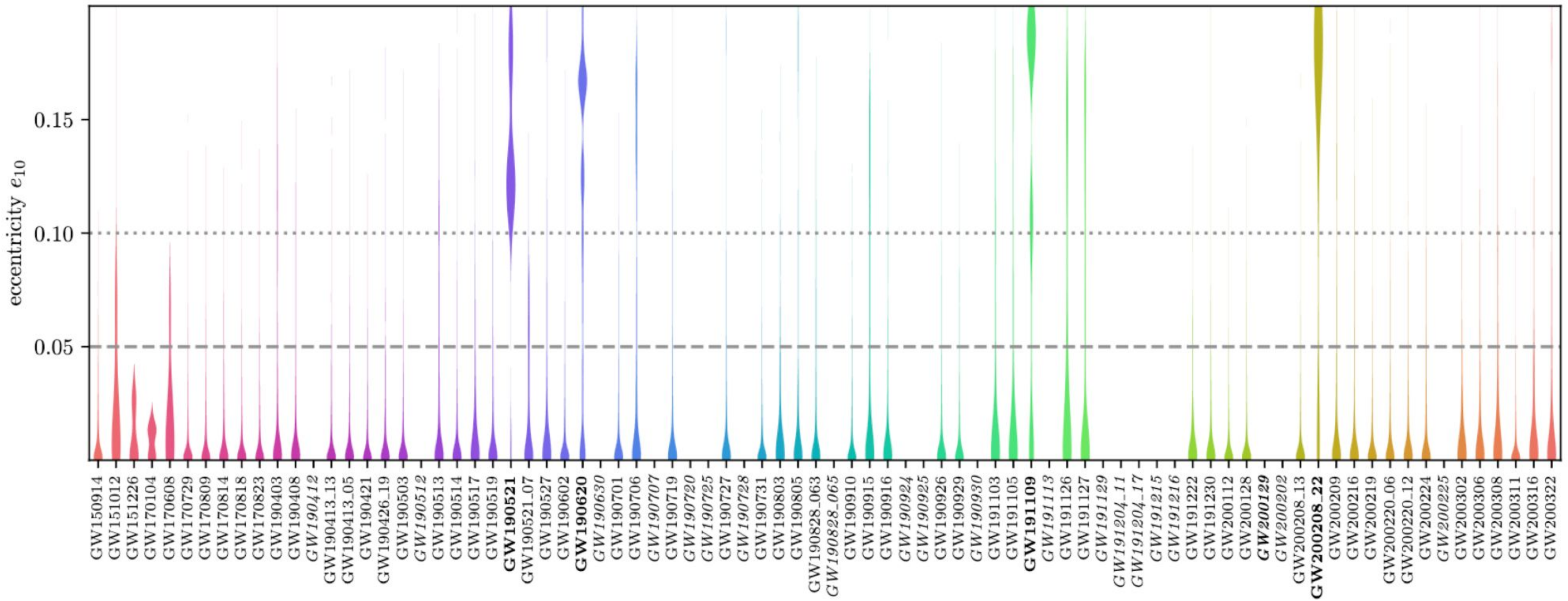
[S V Dhurandhar, Pramana - J. Phys., 2004].

Challenges with Eccentric Binary Merger Detection

- Template bank searches cannot be employed to search for GW signals from eccentric binary black hole (eBBH) mergers.
  - Lack of accurate eccentric waveform templates.
  - Circular template bank -> loss in signal-to-noise ratio significant for $e>0.1$ *[Brown and Zimmerman Phys. Rev. D, 2010]*.
- Eccentricity: time dependent quantity.
  - Must be defined at a reference frequency.
- Eccentricity definition not standardized yet, varies between different waveform models as well as astrophysical models.

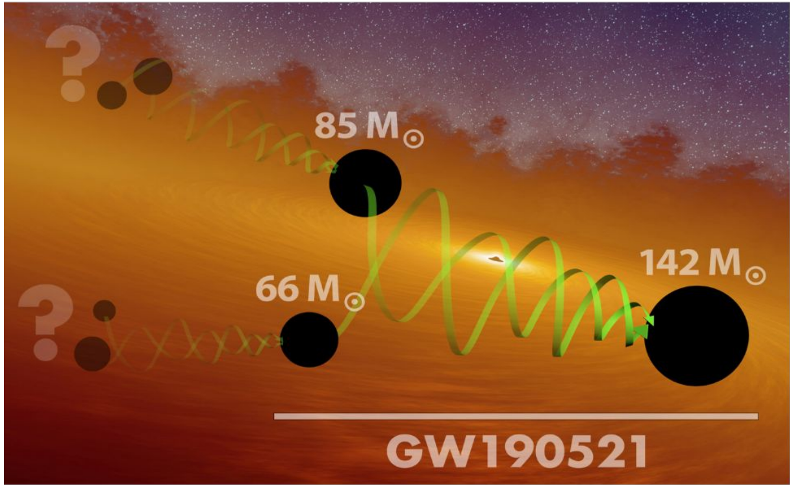
Signatures of Eccentricity in GWTC-3

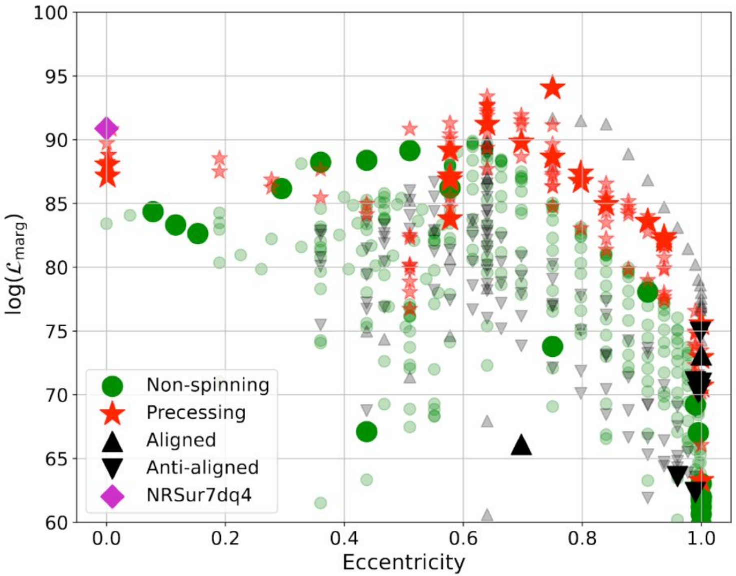
[Romero-Shaw et al. ApJ, 2022]



- At least 4 events that show significant support for e > 0.1 at 10 Hz using an aligned-spin eccentric model SEOBNRE.
- Reweighting technique for parameter estimation, higher-order modes excluded from waveform model.

Signatures of Eccentricity in GWTC-3



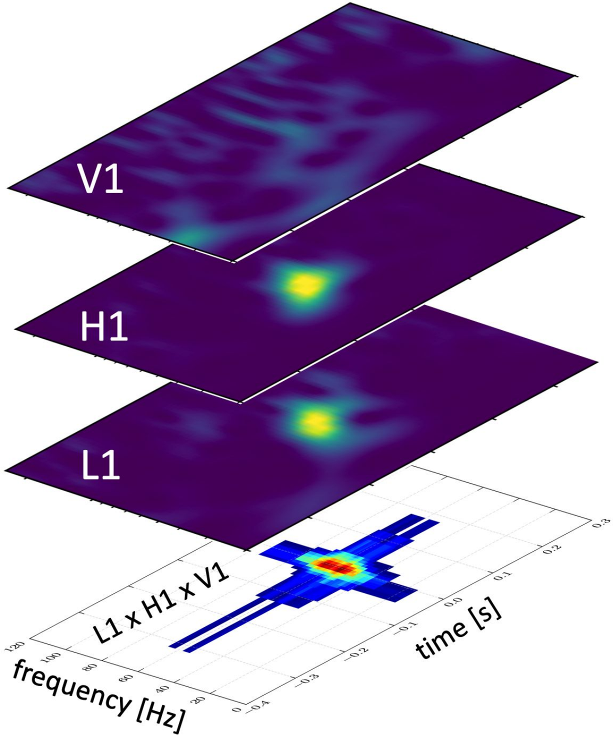


- Parameter estimation was performed with the NR waveforms - authors concluded that this was indeed consistent with an eBBH merger with e~0.7 *[Gayathri, V. et al. Nat Astron, 2022]*.
- Bayesian parameter estimation with semi-analytical waveforms gave similar results *[Gamba, R. et al. Nat Astron, 2022; Romero-Shaw et al. ApjL, 2020]*.

Model-Independent Search

Coherent WaveBurst

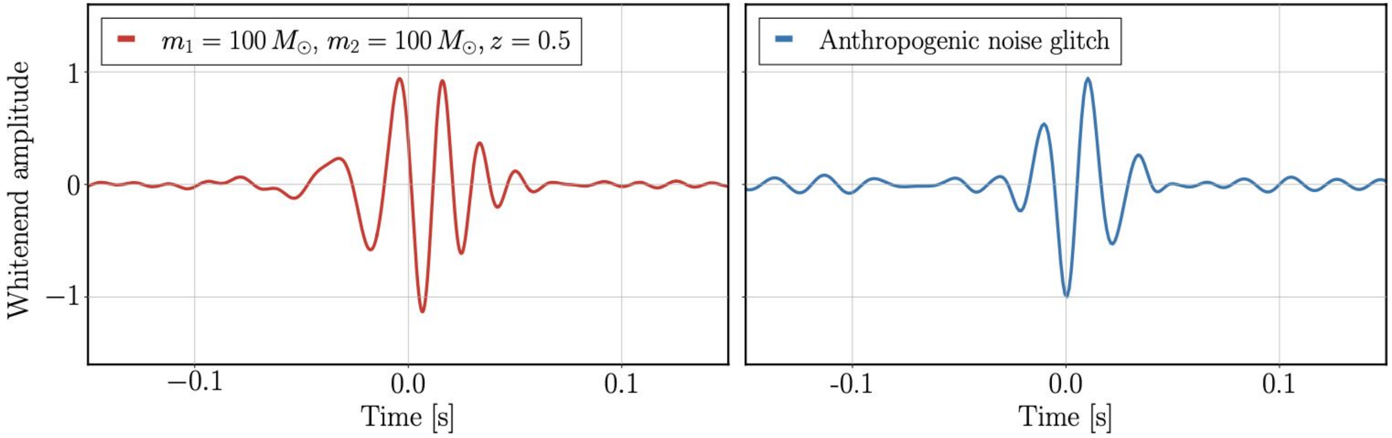
- Coherent WaveBurst (cWB) is a model-agnostic search algorithm [S. Klimenko+ 2008, S. Klimenko+ 2016].
- cWB maps generic properties of GW events into summary statistics.
- Gravitational Wave (GW) signals can be mimicked by short duration detector glitches.
- The standard veto method uses a priori defined thresholds on the cWB summary statistics to distinguish between a GW signal and noise.



Excess power in time-frequency domain
[GW190521 webinar]

Detection Confidence

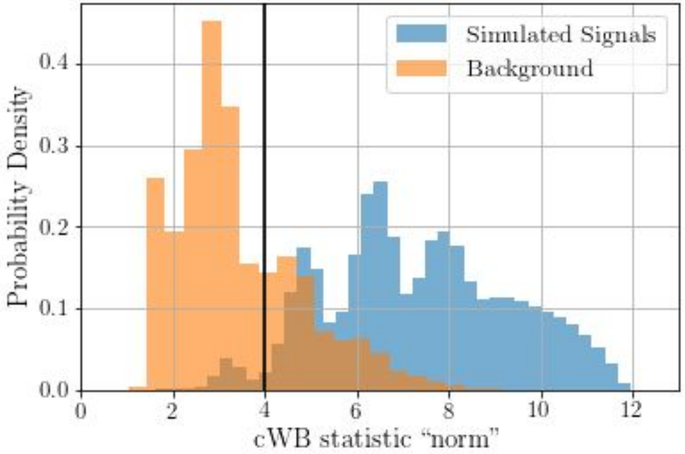
- The detection confidence can be compromised by the presence of non-Gaussian noise transients and instrumental noise known as **glitches**.



High mass BBH and anthropogenic noise glitch comparison *[Brendan O’Brien, PhD Thesis]*.

- High mass BBH signals are of shorter duration and exhibit mostly the merger-ringdown parts in the LIGO sensitive frequency band.
- Lack of inspiral makes the signal prone to be mimicked by instrumental and other non-Gaussian glitches.
- In cWB we employ the veto method to separate noise and GW signals.

Separation of Signal from Glitches



Standard veto method illustration *[Shubhagata Bhaumik, UF LIGO]*.

- All events below the a priori defined thresholds are discarded as noise. Example of a standard veto: ***norm*** > 4.0 where ***norm*** is the ratio of reconstructed energy to total energy, a summary statistic estimated by cWB.
- Designing the vetoes in the multidimensional summary statistics space is time consuming and complex.
- The vetoes need redefinition for each observing run and detector network.

Search for eBBH in LIGO and Virgo's O3 Run

Goals of the O3 eBBH Search:

- Optimize search algorithms for GW signals from eBBH systems.
- Carry out search in O3 data.
- Perform follow-up analysis for interesting events.
- Astrophysical interpretation of search results.

OPEN ACCESS

Search for Eccentric Black Hole Coalescences during the Third Observing Run of LIGO and Virgo

A. G. Abac[1], R. Abbott[2], H. Abe[3], F. Acernese[4,5], K. Ackley[6], C. Adamcewicz[7], S. Adhicary[8], N. Adhikari[9], R. X. Adhikari[2], V. K. Adkins[10] Show full author list

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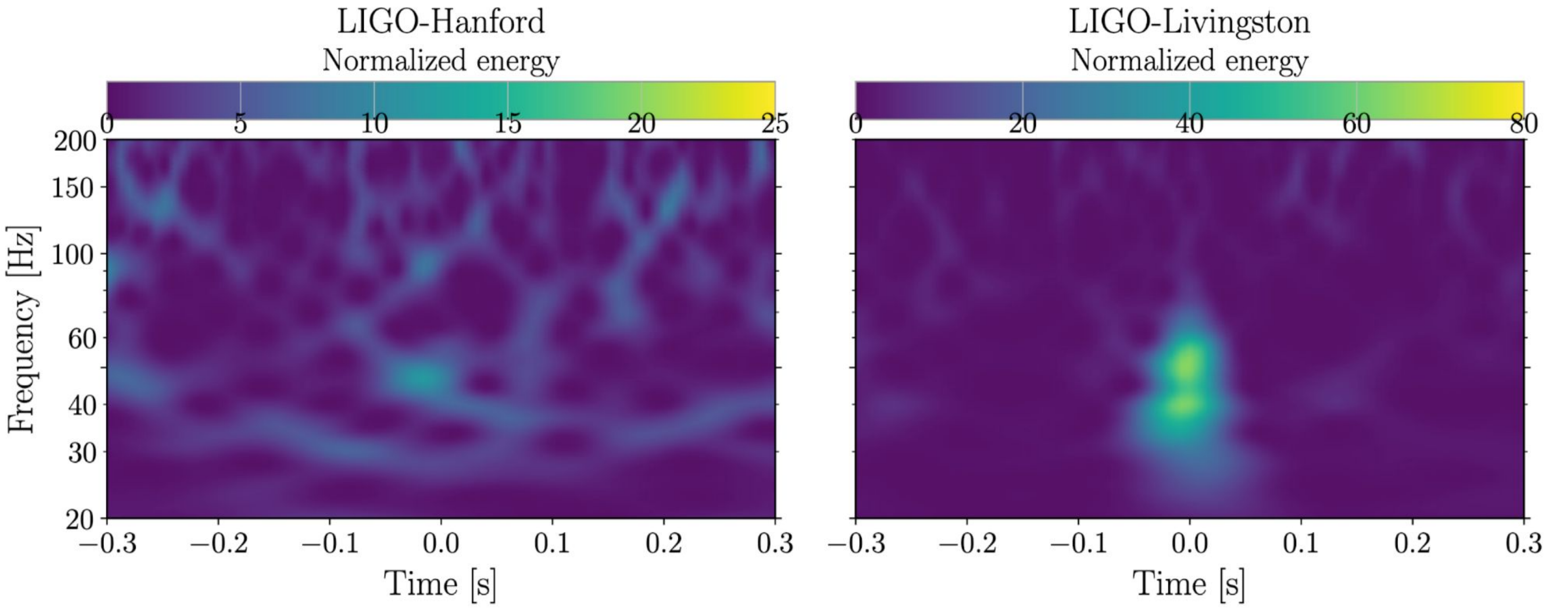
Citation A. G. Abac *et al* 2024 *ApJ* **973** 132

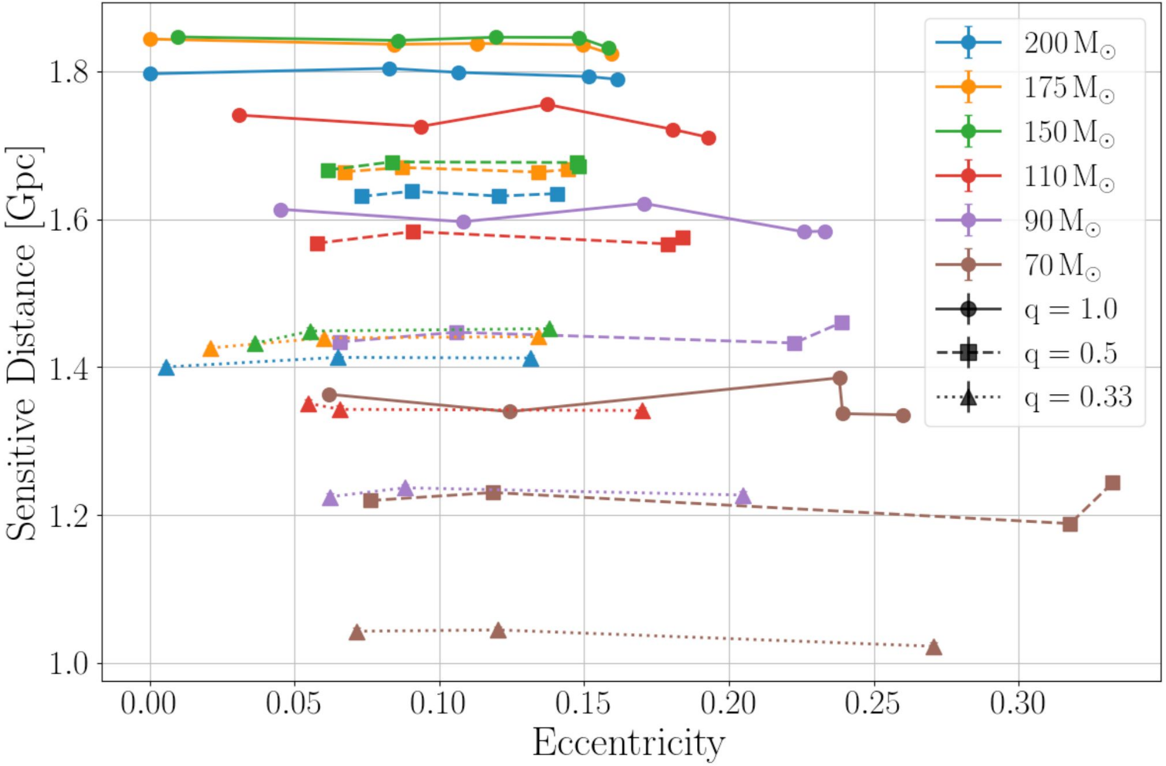
DOI 10.3847/1538-4357/ad65ce

Search Results



One new event (**S190706an**) not detected by other pipelines with Inverse False Alarm Rate (IFAR) = 1.32 yr.

Search Sensitivity



NR Waveforms from the SXS Catalog

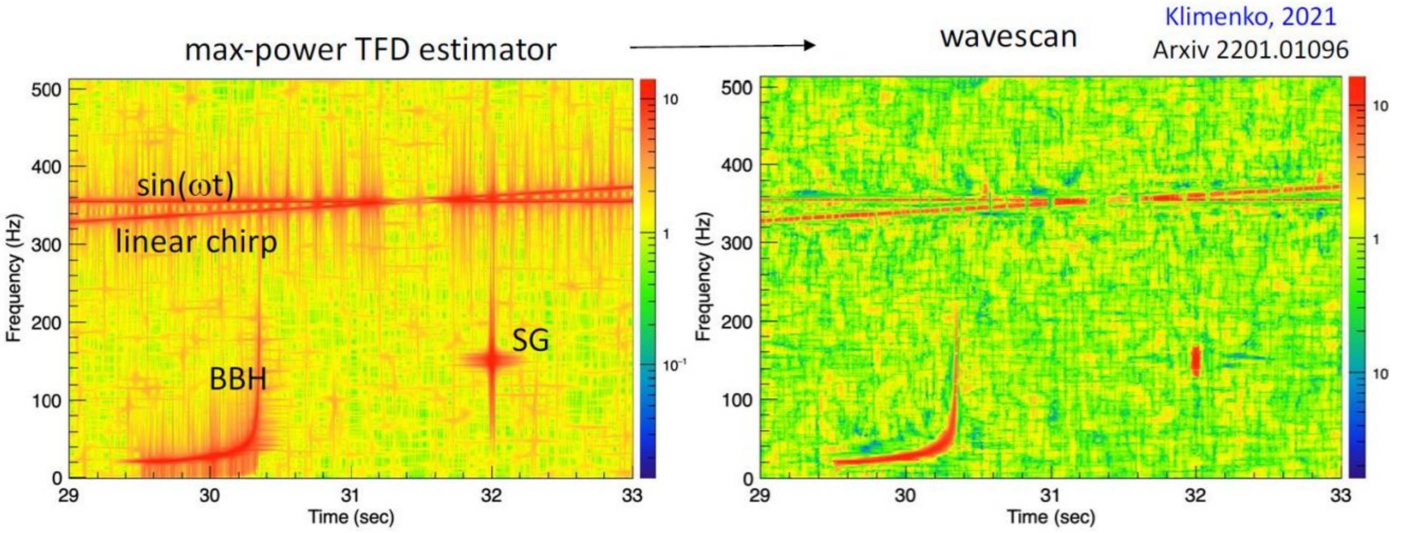
- Total source-frame mass: [70 M⊙, 200 M⊙].
- Eccentricity e in [0.0, 0.3].
- Mass ratio q (m2/m1) = {0.33, 0.5, 1.0}.
- Non-spinning systems.

Sensitive volume-time was used to place **constraints on merger rates** for different formation scenarios.

How did we take this to the next level?

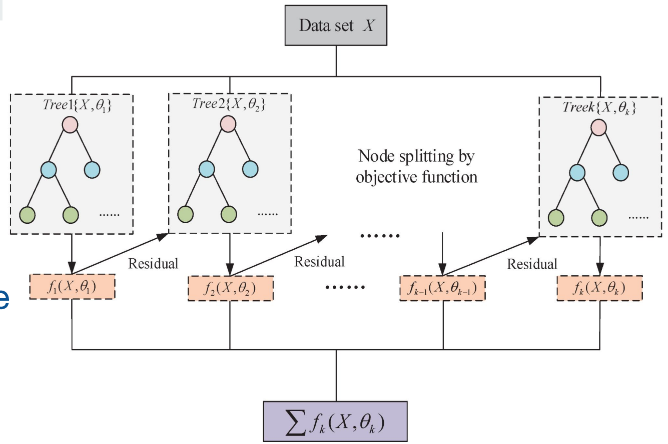
cWB upgrade for O4 - *WaveScan*

- New time-frequency (TF) transform based on wavescan [S Klimenko 2022].
  - High-resolution TF maps with suppression of temporal and spectral leakage.
- Both cross-power and excess-power statistics used for efficient selection of transient events.

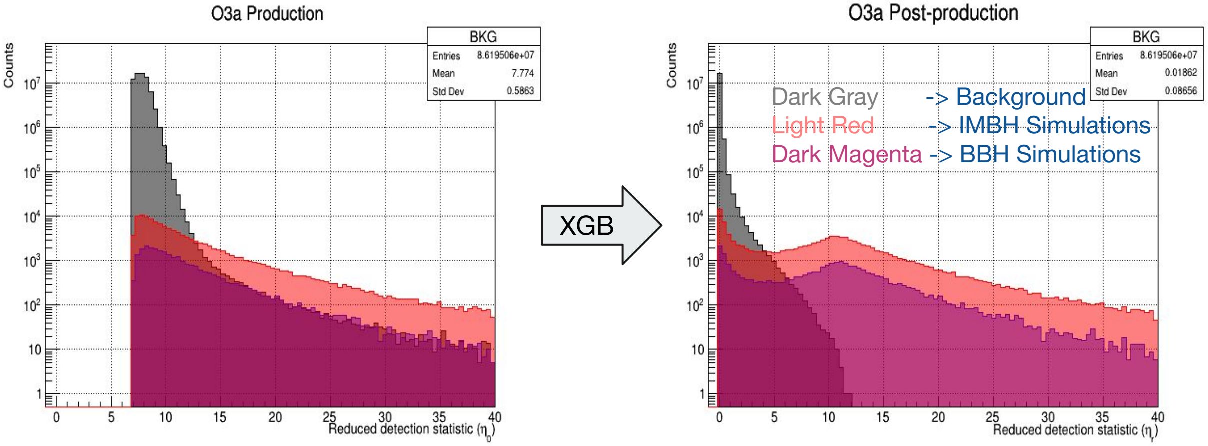


cWB upgrade for O4 - *Machine Learning*

- Subset of summary statistics used as input features for the ML algorithm **XGBoost** - a boosted decision-tree based ensemble learning classifier algorithm.
- Single XGB model is trained to identify both stellar mass and intermediate mass binary black hole (BBH) mergers: Combined BBH-IMBH search.



XGBoost flow chart for building an ensemble of trees. [Rui Guo+ 2020]



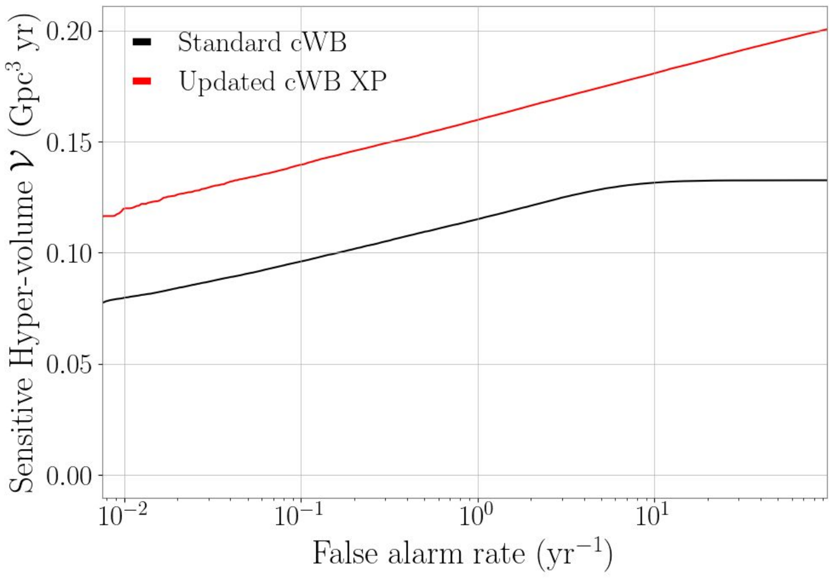
Reduced detection statistic:

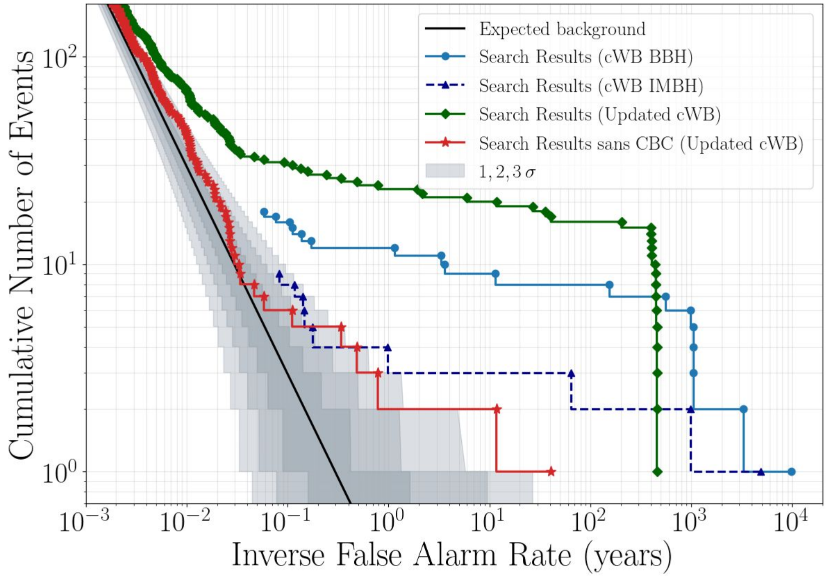
$$\eta_{\mathrm{r}} = \eta_0 \cdot W_{\mathrm{XGB}}$$

W_{XGB} is the penalty factor provided by the ML algorithm [T. Mishra+ 2021, T. Mishra+ 2022].

η_0 is the cWB detection statistic based on the coherent energy.

Search Results on O3

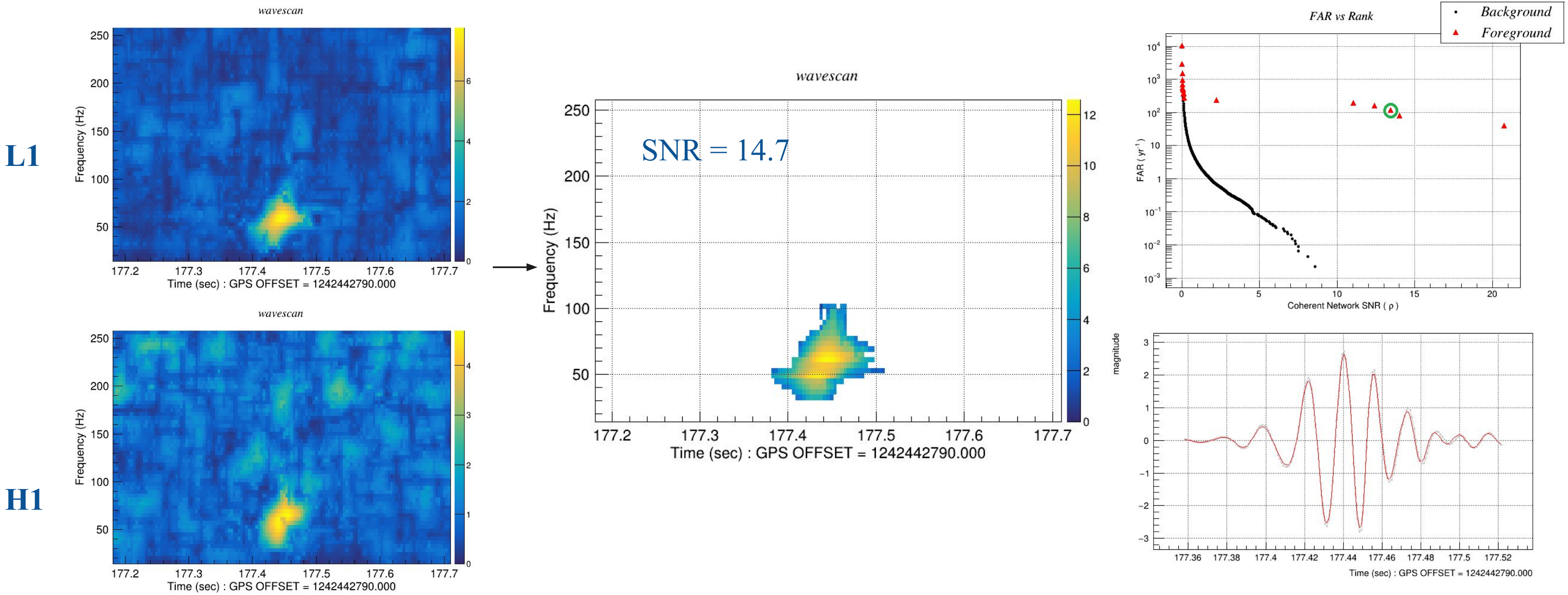




- Improved detection efficiency by approximately **~40% at IFAR>1yr** for all BBH simulations as compared to the standard (2G) cWB search.
- GW events detected with equivalent or **higher significance** including **GW190521**.
- **3 new cWB-only events** detected with IFAR > 1yr.

GW190521 IMBH event

- First conclusive evidence of IMBH.
  - Detected by **cWB with highest significance** as compared to template-based searches.



Fourth Observing Run (O4)

- The updated cWB was used in the low latency searches during the first half of the fourth observing run (O4a) **[May 2023 - Jan 2024]**.
    - Out of the 81 significant detection candidates in O4a *[Public Alerts GraceDB]*, the Online cWB search detected 57 (70% of all significant detections).
- Offline analysis for O4a in progress.
- O4b has started **[May 2024 - ~ 2025/26]**.

Summary

- Model-independent searches like Coherent WaveBurst (cWB) are crucial in detecting GW signals from **uncommon sources like IMBH mergers**.
- Optimized search using cWB was performed for **eBBH signals** in O3.
- cWB was recently upgraded with ***WaveScan***, and now employs an **ML method**, resulting in a **~40% improvement** for BBH signals.
    - Updated cWB search sees **new BBH events** not detected by other LVK searches.
- O4 run underway: **Detected 70%** of 81 significant detection candidates in O4a.
- Possibility of detecting GWs from unexpected and exotic sources like eccentric binary mergers, hyperbolic encounters, unequal mass ratio mergers, Core-collapse SN (CCSN), and so on!

Thank You.

For more exciting GW research contact Prof. Marek Szczepanczyk!

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